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Enhancement of Fatigue Strength on SAE 1541 Steel Link Plate with Slip Ball Burnishing Technique

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ABSTRACT

This research paper describes a technique for the enhancement of the fatigue strength of the chain link plate in the drive system of a military armoured vehicle. SAE 1541 steel link plates of chains were subjected to cyclical tensile stress due to repeated loading and un-loading conditions. The crack was getting originated from the pitch hole and growth perpendicular to the chain pulling load, due to fatigue mechanism. In general plate holes are manufactured using the conventional process. An additional novel technique called the slip ball burnishing (SBB) method is applied for improving the hole properties. The improvement is made by producing local plastic deformation, improving surface finish and compressive residual stress throughout in the pierced hole. Both the conventional process (CP) and the SBB technique have been evaluated by optical, profile, surface roughness and micro harness tests. Experimental fatigue test validations were done in both chain samples using the Johnson-Goodman method. SBB chains passed $3x10^6$ cycles at the load of 17.61 kN and CP chains passed $3x10^6$ cycles at the load of 13.92 kN. The conclusion was that SBB made a significant improvement of 26.51 per cent of fatigue strength compared to CP.

Keywords: Fatigue test; Slip ball burnishing; Compressive residual stress; Micro hardness; Surface roughness

1. INTRODUCTION

Chain is a reliable machine element for transmitting power. The chain link plate should have static tensile strength and also the ability to withstand up to the dynamic load. The FEM result confirms the fatigue crack of the plate originated at a certain point at 90° of the pitch hole[1]. Stress obtained is maximum in that position. Chain plate with C40 grade was frequently failed in draw bench application, due to crack initiation of fatigue in hole[2] surface and tracked by transgranular brittle overload fracture. Chain link plate made up of SAE 1045 and crack were seen adjacent to the bore diameter of the pitch hole[3]. The repeated cycle load led to the initiation of the fatigue crack from the pitch hole and the propagation perpendicular to the chain pulling load. The Research papers pay attention mostly on failure analysis of chain parts, experimental testing on wear and tensile strength[4-7] and not seen in the area of chain fatigue strength study and improvement.

ANSI 80H chain link plates were subjected to minimum fatigue strength of 10.70 kN as reported in standard ISO 606. The link plates were manufactured using the conventional piercing process. The operation consists of roll over, shear, fracture and burr zones as shown in Fig. 1(a). Two step joined processes of piercing and shaving[8] in SK85 material with good hole quality were proposed.

In the roller chain assembly, the bush and bearing pin were in contact with shear zone of holes in the inner link plate and the outer link plate respectively as shown in Fig. 1(b). The link plates were subjected to cyclic load. The low shear area in link plates caused a reduction in the contact surface, creating uneven bending stress and shear stress in the bush and bearing pin. Basically factors affecting the fatigue strength are stress concentration, surface condition and surface roughness.

The Ball burnishing process is explicated using the experimental method and used in external surfaces of aluminium 6061[9], AISI 1045[10] and aluminium 2017A-T451[11] materials. An armor steel MIL-A-12560, tempered martensitic structure with 38 HRC[12] and armor piercing 7.62 mm was used for the ballistic test. After the test, a small grain size was observed in the hole zone this was due to recrystallisation and high plastic deformation. The estimated fatigue life of on EN 19 grade gear[13] working under fluctuated loads used in fighting vehicle and results are plotted in S-N curve.

2. METHODOLOGY

In this study, an ANSI 80H simplex roller chain link plate was designated for the experimentation. The link plates were made of SAE 1541 material grade. The first method was the conventional process (CP). Inner link and outer link plates were manufactured using the conventional blanking, piercing, shaving, heat treatment and shot peened process respectively.

The second method was slip ball burnishing (SBB) technique. The inner link and outer link plates were manufactured using the conventional blanking, piercing, shaving, heat treatment, shot peened and additional SBB process respectively. The same raw material is used in the two methods.

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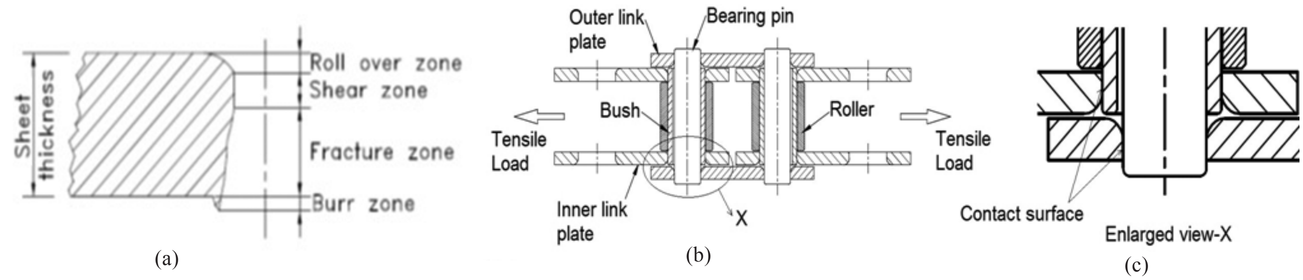

Figure 1. (a) Different zones of conventional piercing process, (b) Roller chain assembly and enlarged view of bush, bearing pin contact surface with link plates.

The design parameters in the SBB technique were the burnishing force, the feed rate, ball diameter, link plate hole diameter before and after SBB technique described in the discussion part. Four test methods were used for the evaluation of the hole surface of link plate. They were optical, profile, roughness, and micro harness traverse survey.

Simulation analysis was carried out for the fatigue life cycle in the solid works software. Johnson Goodman formula was used in the calculation of the maximum test force, is described in fatigue testing 3.3. Sample chains were produced in each method for fatigue testing validation. Fatigue tests were conducted in various test loads and plotted in load *vs* cycles (S-N) graph.

2.1 Slip Ball Burnishing Technique

In piercing and shaving, shear zone was improved upto a maximum of 60 per cent of the work piece thickness (T). A novel technique called SBB has been proposed for a further improvement.

SBB is a mechanical surface finishing process, performed on link plates to enrich their mechanical properties, and enhancing their performance to extremely tough working environments. Grinding, precision turning, reaming, honing and lapping were some of the other surface finishing processes. The above other process surface finishing was achieved by material removal. There is no removal of material involved in SBB. Application of pressure over the ball on the metallic hole surface caused the occurrence of plastic deformation and inducement of a significant residual compressive stress.

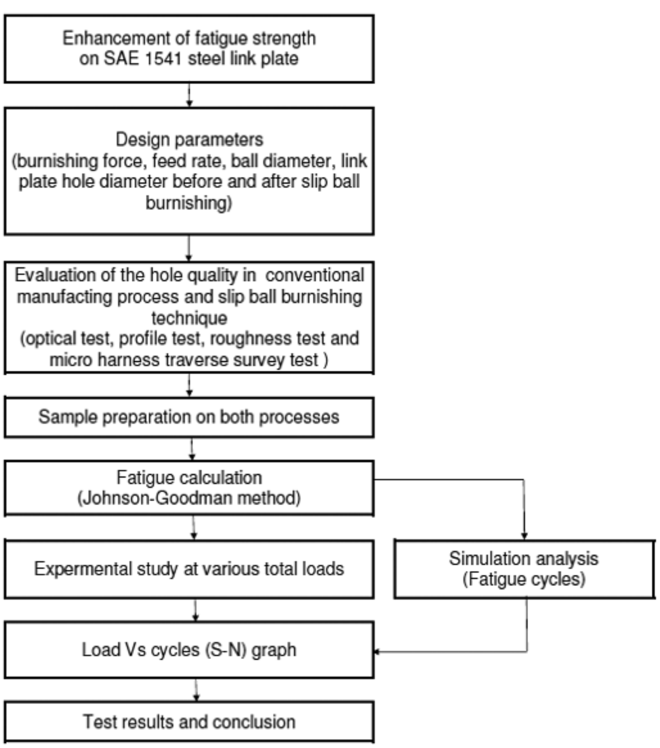

Figure 2. Experimental methodology.

Many researches are engaged in the area of improvement of the surface finish, wear and corrosion resistance. In this experimental study SBB is implemented for surface finish to enhance the fatigue strength of link plate.

In this new experimental research work, SBB novel technique was used to improving the fatigue strength of the link plate. The ball was pressed through the harden link plate pitch hole as shown in Fig. 3(d). Circumference of the ball surface was slipped the contact with the hole surface.

SBB technique is in the form of a linear process.

Here the linear system equation is

$$y = mx + c \tag{1}$$

y = Output of the process, x = Input of the process, m and c are constants based on the material properties.

here

$y = d_f - d_i$ = Output plastic deformation

$x = d_b - d_i$ = Interference

d_b = Ball diameter, d_i = Hole diameter before SBB, d_f = Hole diameter after SBB.

The ball diameter should be over sized than finished hole size due to interference.

$d_b > d_f$

Rearranged Eqn. (1) as

$$d_f - d_i = m\,(d_b - d_i) + c \tag{2}$$

2.2 Materials

Specifications of the ball:

Material : Tungsten carbide

Chemical composition : Tungsten carbide 93 % and Cobalt 7 %

Mechanical properties of tungsten carbide:

Hardness : 91.1 HRA (77 HRC)

Density : 14.95 gm/cc

Transverse rupture strength: 410,000 psi

Porosity : A02, B00, C00 (Max.)

Grain Size : Coarse

Specifications of the link plate:

Material Grade : SAE 1541

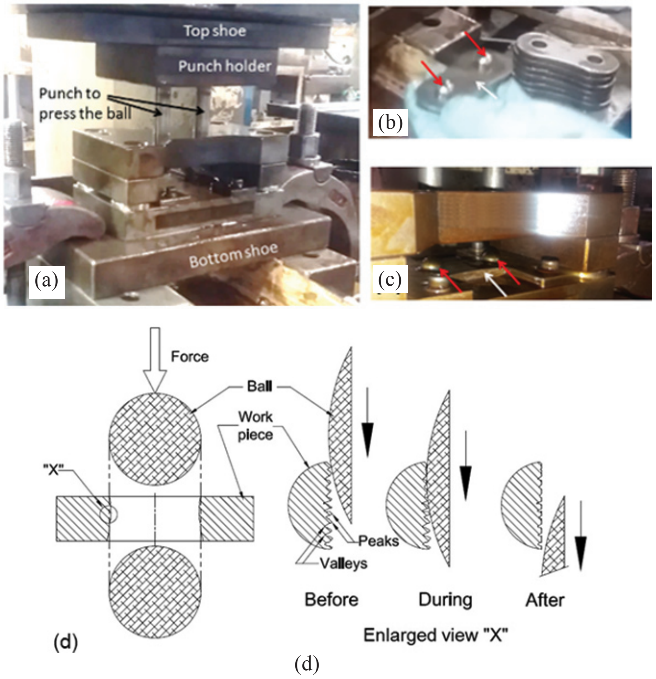

Figure 3. (a) SBB tool setup, (b) Link plate with balls, red color arrows indicates the balls and white color arrow indicate the link plate, (c) Link plate and balls are placed in the tool setup, (d) Schematic representation of SBB technique.

Hardness : 41 to 46 Hrc
Micro structure : Tempered martensite
SBB force calculation for a single ball:
SBB force,

$$P_Y = \pi\ \varepsilon\ H\ R^2 \quad (3)$$

where

ε = Relative depth of penetration = 0.045
d_b = Ball diameter = 7.92 mm
R = Ball radius = 7.92/2 = 3.96 mm
H = Vickers hardness of link plate = 413 HV (converted from 42 Hrc)
P_Y = 3.14 x 0.045 x 413 x 3.96 x 3.96 = 915.13 kg

Taking maximum burnishing force for a single ball (consider 20 % higher than force)

P_Y = 1.2 x 915.13 = 1098.16 kg.

Specifications of the machine:
Press type: Mechanical press
Press capacity: 20 Ton
Power: 2 HP
Bed size: 350 mm x 400 mm
Burnishing force: 20 Ton
SBB feed rate: 60 mm/1.09 s

The SBB tool setup is shown in Fig. 3(a). The tool setup consists of a top shoe, a punch holder with punch, a component link plate locator, a die and a bottom shoe. Two punches were used for forcing the balls. Two Tungsten carbide balls were placed in link plate holes and located manually in the press tool as shown in Figs. 3(b) and 3(c). The total tool setup was clamped in mechanical press.

3. RESULTS AND DISCUSSION

Linear process parameters of SBB are shown in the Table 1.

3.1 Evaluation of Hole Surface of the Link Plate

Four test methods were used for the evaluation of the hole surface of the link plate. They were optical, profile, roughness, and micro harness traverse survey.

3.1.1 Optical Test

Two link plates were cut through the hole and examined by using an optical microscope Leica EC3. The overall link plate thickness was 4mm. Comparisons between the two link plates are shown in Figs. 4(a) and 4(b). The shear zone length observed in the CP was in the range between 2.14 mm to 2.43mm. The shear zone length observed in the SBB was in the range between 3.01 mm to 3.33 mm. There was an increase in the shear zone length in SBB.

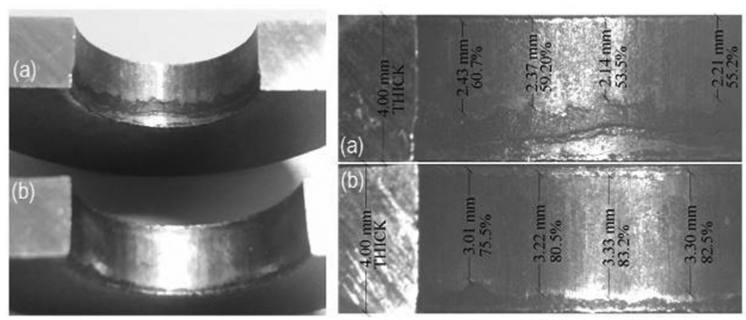

Figure 4. Photograph of the link plate of (a) CP with shear zone length (in mm) and % w.r.t. to thick, (b) SBB with shear zone length (in mm) and % w.r.t. to thick.

3.1.2 Profile Test

Shear zone of the samples were measured using Zeiss contoure cord 1700SD instrument for finding the hole straightness line profile as shown in Figs. 5(a) and 5(b). In CP 2.279 mm straight line was observed and 3.267 mm straight line was observed in SBB. There was an increase in the straight line profile in SBB.

3.1.3 Roughness Test

Surface roughness of hole length was measured using Surfcom 130A –Zeiss tester as shown in Fig. 5(c) and 5(d). Ra

Table 1. Specifications of SBB

Link plate	Ball diameter (d_b) mm	Maximum SBB force (one ball) (P_y) kg	Hole diameter before SBB (d_i) mm	Hole diameter after SBB (d_f) mm	Output plastic deformation (y) mm	Interference (x) mm
Outer plate	7.92	1098.16	7.73	7.82	0.09	0.19
Inner plate	11.59	2351.69	11.41	11.50	0.09	0.18

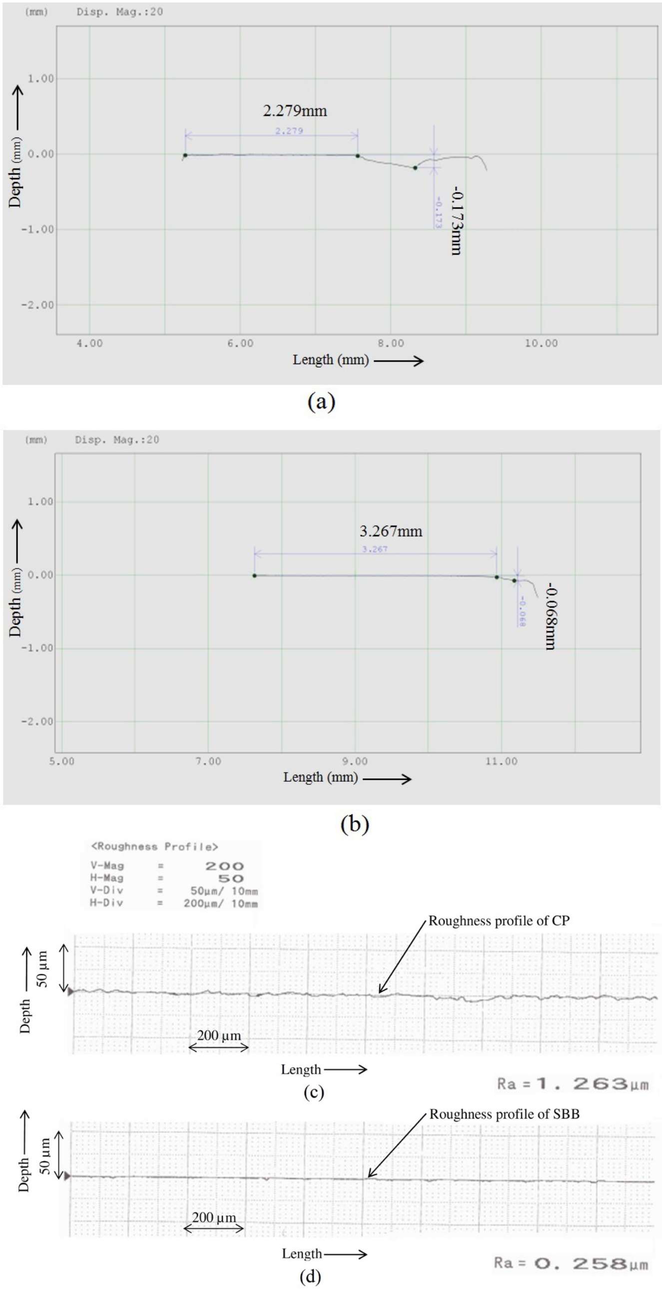

Figure 5. Hole straightness line profile of (a) CP, (b) SBB and Roughness of (c) CP, and (d) SBB.

refers to arithmetic mean deviation of the surface roughness. Ra value of CP was 1.263 µm and SBB was 0.258 µm. surface roughness of SBB was better-quality than CP.

3.1.4 Micro Hardness Traverse Survey Test

Hole surface micro hardness in CP and SBB was analysed using a Future-Tech micro hardness tester FM-800 and microstructure was analysed using a Leica DMC2900 microscope. Figs. 6(a) and 6(b) show that of surface hardness in CP as in a lower level. After SBB the surface hardness was increased up to 13 HV@0.20 kg in the depth of 0.03 mm. The increase in surface hardness was based on the interference between the ball and hole, due to compressive residual stress and due to plastic deformation.

3.2 Simulation Analysis

3.2.1 FEA Analysis

FEA analysis on fatigue cycle was carried out by solid works on a single link plate with CP and SBB as shown in Figs. 7(a) and 7(b). SAE 1541 material properties were entered in the input. 8386 nodes and 8993 nodes were generated to mesh the link plates of CP and SBB, respectively. The top hole surface in the link plate was a fixed support and load was applied in the bottom hole surface towards the X direction.

At a load of 14.925 kN on a single plate (which was considered as half of 29.85 kN load in chain) CP crossed from a minimum 28396 cycles to a maximum 1000000 cycles. At the same load, SBB crossed from a minimum 212561 cycles to a maximum 1000000 cycles.

3.3 Fatigue Testing

Fatigue tests were conducted using an Amsler 250 kN fatigue testing machine. The tests were validated under fluctuating tension condition and force was applied in the longitudinal direction of the chain as shown in Fig. 8(a). The universal fixtures were designed according to the ANSI 80H chain dimensions. Seven pitches included five free pitches were used. The first pitch and seventh pitch were fixed in the top and bottom fixtures respectively.

Sample chains were tested as per the ISO 15654 fatigue test method for transmission precision roller chains. The maximum test force F_{max} was determined using the Johnson

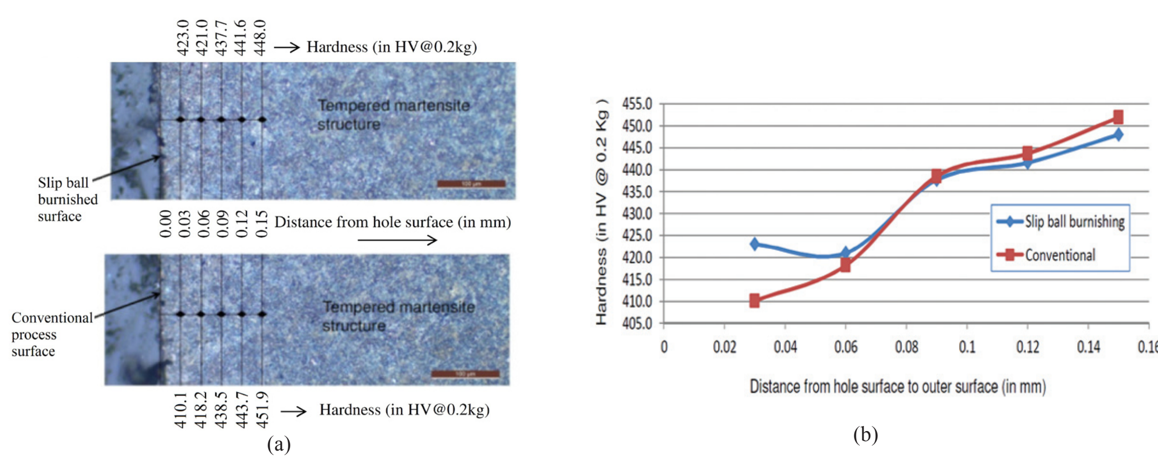

Figure 6. (a) Micro structure and hardness traverse from hole surface (200X) and (b) Graph of hardness versus distance.

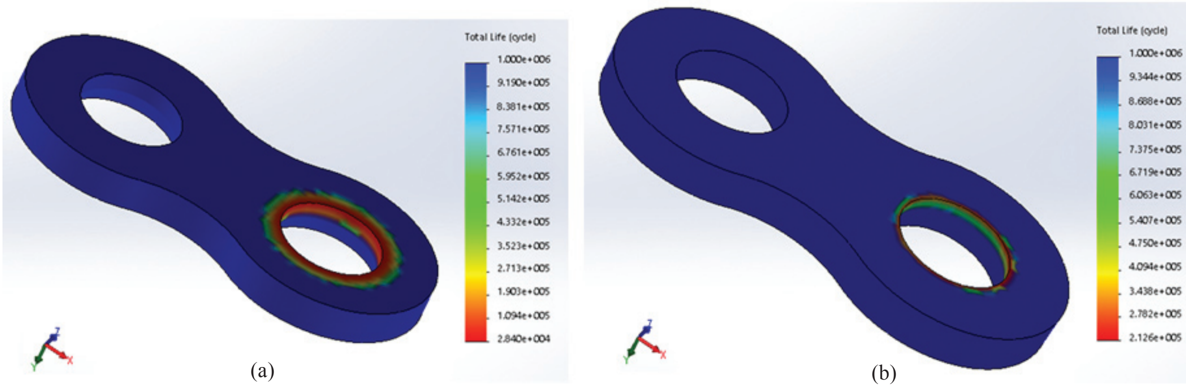

Figure 7. FEA analysis on Fatigue life cycles at a load of 14.925 kN in a single plate (a) CP and (b) SBB.

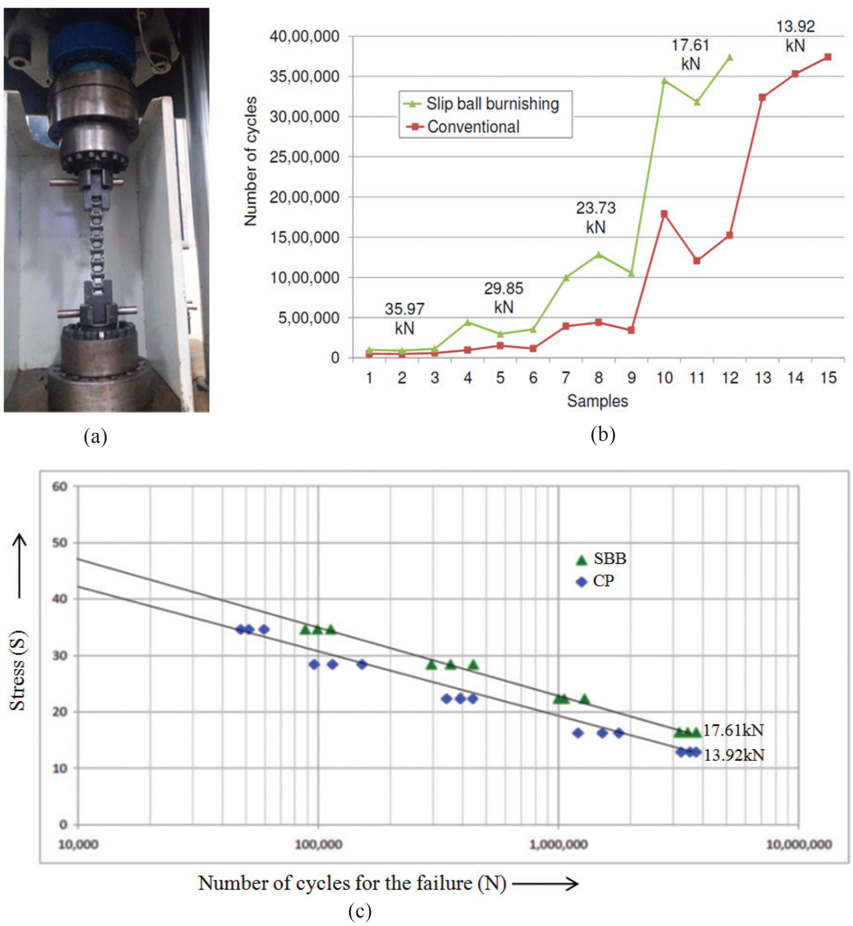

Figure 8. (a) Fatigue testing machine setup, (b) Number of cycles *vs* samples at various total loads, and (c) Stress *vs* numbers of cycles for the failure (S-N) graph for SBB and CP.

Goodman relationship:

$$F_{max} = \frac{F_d F_u + \left[F_{min}\left(F_u - F_d\right)\right]}{F_u} \tag{4}$$

where F_{max} = maximum total load, F_{min} = minimum load, F_u = minimum ultimate tensile strength of 80 H chain is 55.60 kN as specified in ISO 606, F_d = test load.

The chain should withstand 3 million cycles without failure. Staircase technique was used for fatigue testing. Three samples from every total test loads were tested for the purpose of comparison. The minimum fatigue strength of ANSI 80H simplex roller chain in ISO 606 standard reported was 10.7 kN. Fatigue tests were carried out for various total loads.

Samples 1-3 tested at 35.97 kN, 4-6 tested at 29.85 kN, 7-9 tested at 23.73 kN, 10-12 tested at 17.61 kN and 13-15 tested at 13.92 kN are shown in Fig. 8(b) and Table 2. SBB chains for each load showed a performance better than CP. The values based on the test results have been plotted in S-N graph, as shown in Fig. 8(c). SBB chains passed $3x10^6$ cycles at the load of 17.61 kN and CP chains passed $3x10^6$ cycles at the load of 13.92 kN.

The higher hole contact area in the link plate and the significant residual compressive stress by the SBB, caused transfer of stress distributions equally throughout the pitch hole surface. This helped a better performance in all SBB than CP at different test loads.

4. CONCLUSIONS

In this research paper, the effect of slip ball burnishing (SBB) technique has been studied and performance results compared with conventional process (CP). The conclusions drawn are;

- In the optical test 0.87 mm and profile test 0.99 mm were increased in SBB compared to CP.
- In the roughness test Ra value 0.258 µm in SBB was very superior compared to CP.
- In the harness traverse survey test, there was an increase in the micro hardness up to 13 Hv in SBB compared to CP.
- In FEA analysis, SBB passed a minimum 212561 fatigue cycles and CP passed a minimum 28396 fatigue cycles. There were increases in fatigue life cycles caused by SBB.
- In Fatigue test validation, fatigue strength of the SBB was 17.61 kN, whereas it was 13.92 kN in CP. It was found that 26.51 % of fatigue strength was improved by SBB. The conclusion based on the experimental results was that the fatigue strength of link plate was enhanced by SBB novel technique.

Table 2. Fatigue test details

Sample number	Minimum ultimate tensile strength of chain (F_u) in kN	Maximum total load (F_{max}) in kN	Maximum total load (in % of minimum ultimate tensile strength)	Minimum load (F_{min}) in kN	Test load (F_d) in kN	Conventional (*CP*) Number of cycles for the failure	Slip ball burnishing (SBB) number of cycles for the failure
1	55.6	35.97		3.597	34.612	51,545	99,243
2	55.6	35.97	64.69	3.597	34.612	47,610	88,360
3	55.6	35.97		3.597	34.612	59,568	1,12,863
4	55.6	29.85		2.985	28.389	96,287	4,42,123
5	55.6	29.85	53.69	2.985	28.389	1,52,459	2,96,023
6	55.6	29.85		2.985	28.389	1,14,840	3,55,487
7	55.6	23.73		2.373	22.309	3,90,686	10,00,014
8	55.6	23.73	42.68	2.373	22.309	4,40,686	12,82,898
9	55.6	23.73		2.373	22.309	3,42,446	10,55,224
10	55.6	17.61		1.761	16.367	17,86,834	34,50,008
11	55.6	17.61	31.67	1.761	16.367	12,06,834	31,84,556
12	55.6	17.61		1.761	16.367	15,24,900	37,40,035
13	55.6	13.92		1.392	12.850	32,40,015	#
14	55.6	13.92	25.04	1.392	12.850	35,30,013	#
15	55.6	13.92		1.392	12.850	37,40,013	#

Fatigue tests not conducted in SBB at 13.92 kN, because SBB already passed 3×10^6 cycles at the higher load of 17.61 kN.

- SBB chains with high fatigue strength can be used for heavy shock load applications like skid-steer loader, army bradley fighter, mining crawler drill rigs. In general, the SBB technique can be used in products like holes of automobile connecting rods, pump valves.

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Contribution in the current study, he did design, development, testing and evaluation of link plate, modification(s) and fatigue tests.

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Contribution in the current study, he guided the project, interpretation of results and testing data, finalising the configuration, analysis, paper writing and review of this paper.